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Niall Holmes

Technological University Dublin, niall.holmes@tudublin.ie

Roger West

Queen's University - Belfast

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Finite Element Modelling of Moisture Movement in Concrete Floors

Mr. Niall Holmes and Dr. Roger P. West

Abstract

Predictive methods for determining the point at which it is safe to apply floor coverings to concrete floors can save time and money for the client, contractor and the floor installer. The current standard states that impervious floor coverings should not be applied until the surface of the floor reaches a relative humidity (RH) of 75%, established using a surface hygrometer test. Tests at Trinity College Dublin on drying concrete slabs in natural and forced drying environments show that there is a large variation in the residue of moisture deep in the concrete when the floor covering is applied, particularly so in a forced drying environment [1]. When an impermeable floor covering is applied to the floor surface, this residue of moisture will gradually equilibrate and generate (over a long time) a vapour pressure that can result in substantial damage to the covering, resulting in expensive repair work.

This paper presents a finite element model that predicts the changing moisture content, in terms of the internal RH, during drying and after the application of the floor covering as the internal RH equilibrates over time. The model accounts for the thickness of the slab, w/c ratio, environmental conditions, boundary conditions and uses nonlinear diffusion coefficients and evaporation rates to accurately model the moisture movement in the slab. The results from the model give good correlations with the experimental readings taken at the various depths over time using hand-held humidity probes.

Keywords: Concrete floor slabs, drying, finite element modelling, moisture movement, moisture redistribution, vapour pressure.

Mr. Niall Holmes graduated with an Honours degree from Queen's University Belfast in 1998 and a Masters degree from Trinity College Dublin in 1999. He is currently a PhD student at Trinity College Dublin where he is researching finite element modelling of moisture migration in concrete during drying.

Dr. Roger P. West is Head of the Civil Engineering Department at Trinity College Dublin. His research interests in concrete lie in durability, rheology and new materials. He is a former Vice-Chairman of the Council of the Irish Concrete Society and is currently the Irish Liaison Engineer for Eurocode 2.

INTRODUCTION

The number of reports of damage to impervious concrete floor coverings has increased over the past 30-years, mainly due to the increase in fast-track construction activities. Building contractors or owners often will not wait for a concrete floor to dry sufficiently and so the floor is installed when the floor is relatively wet. However, after some time, perhaps several months or even years, the tiles begin to rise from the floor or vinyl floor coverings blister. The principal cause of these problems is the residual moisture in the slab on sealing redistributing itself and building up a vapour pressure under the covering. This affects the adhesive of the covering to the floor reducing the bond between it and the floor. Tests used to determine the point in time to apply a floor covering only consider the surface moisture condition and takes no account of the moisture condition deep in the concrete. In the UK, for example, floor coverings are applied when the surface reaches a relative humidity (RH) of 75% as established using a surface hygrometer test [2]. It seems, therefore, that a reliable method that can predict the point to safely apply a covering would be a major advantage to floor installers and contractors alike. This paper presents such a predictive method, in the form of a finite element (FE) model for both the drying stage and the effect of the covering on the residual moisture. This model outputs the moisture content through the depth of the concrete in terms of the internal RH, commonly accepted as a reliable and informative parameter to represent the internal moisture condition.

To assess the changing moisture condition in concrete, a number of concrete slabs (700x700x150mm thick) were made up with varying w/c ratios (0.4, 0.5 and 0.6) and allowed to dry in two distinct drying conditions; a laboratory with normal ambient drying conditions and a controlled room with elevated temperatures and reduced ambient humidities (using a heater and a dehumidifier). The internal RH was measured using a humidity probe attached to a hand-held meter, developed by a Dublin-based company (Tramex Ltd), which outputs the RH on a digital display. The RH was measured at various depths in the slab to view the moisture condition over time. When the slabs reached 75% RH on the surface (according to a surface hygrometer test), an impermeable vinyl floor covering was applied to the concrete. The measurement of the RH at the various depths was continually monitored after the covering was applied. In addition, the pressure development underneath the covering was also monitored using a pore pressure gauge (PDCR 81) attached to a Datascan unit set-up to read the increasing vapour pressure, as a result of the moisture redistribution, at hourly intervals. The results show that there is a continuing gradual increase in the pressure over time, particularly under the coverings for the slabs initially dried in the controlled room with the high moisture residues [3].

FINITE ELEMENT ANALYSIS

In order to model the initial drying process, numerical analysis was performed using a commercial FE package, DIANA, which has the capability of modelling the non-linear diffusion of moisture within the concrete and evaporation from the surface. DIANA is a large-scale general FE system based on advanced database methods, incorporating civil, mechanical and other engineering disciplines, where simple to very complex analysis can be solved easily and quickly using advanced CAD/CAM systems. The input data for a DIANA analysis are given in a normal (ASCII) text file with 80 characters per line, which can be made in various ways; via a text editor or generated by means of a preprocessor program (FEMGV). The input for any type of analysis is given in a series of tables and sub-tables. These tables specify the nodal numbers and coordinates, the element numbers and nodal connectivity, the material and physical properties, special data such as the Gauss number of the elements, the boundary and initial conditions and the time-stepping properties. The command file (*.com) contains user commands, describing what DIANA must do with the FE model, for instance, how to generate, plot and analyse it.

The mesh selected for the analysis is shown in Fig. 1. It consists of 700 8-noded quadrilateral (CQ8HT) elements for diffusion in the concrete and 70 2-noded linear (B2HT) elements at the surface for evaporation. The CQ8HT element (Fig. 2(a)) is an eight-noded quadrilateral isoparametric element for general flow analysis. The B2HT element (Fig. 2(b)) is a two-node isoparametric boundary element used here for evaporation from the surface. As shown, the top 50mm of the slab has a finer mesh as it has been found from the experimental results (and subsequent FE analysis) that the RH in this area is more sensitive to change than that deeper in the concrete, as the influence of evaporation at the surface is greater. The model can be run for any size of time step, and following a sensitivity study, it was found that 10-day steps are sufficient (results within 1.6% as compared with 1-day time steps).

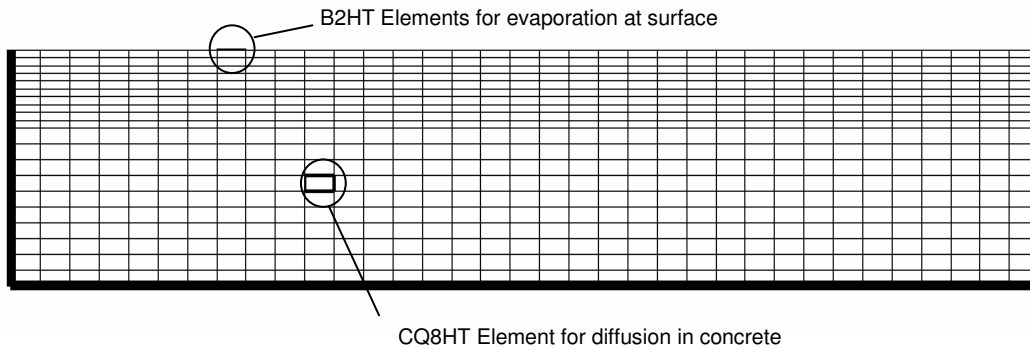
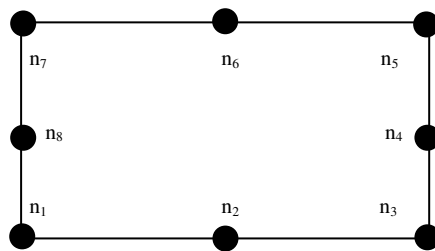
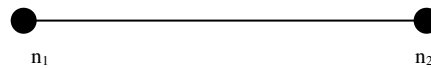


Fig. 1 Mesh set-up for the 700x150mm thick concrete floor slab. Mesh consists of 700 CQ8HT diffusion and 70 B2HT evaporation elements.



(a) CQ8HT



(b) B2HT

Fig. 2 CQ8HT and B2HT elements used to model the diffusion and evaporation in the concrete slab.

Material Properties

The material properties of most importance here are the rate of moisture diffusion through the concrete and the evaporation rate of the moisture through the surface to the surrounding air. The equation to describe the diffusion between two neighbouring nodes in DIANA is given in Eqn. 1, also known as Fick's second law [4] and is commonly accepted to accurately represent the movement of moisture in concrete during drying [5,6]. In Eqn. 1, P is the unknown (here the internal RH) and λ is the diffusion coefficient (m^2/sec) shown as a function of the internal RH. The diffusion coefficient (D) in this analysis is calculated using Eqn. 2, which has been developed from experimentally determined RH profiles in various concrete slabs during drying [6],

$$\frac{\partial P}{\partial t} = \frac{\partial}{\partial x} \left(\lambda(P) \cdot \frac{\partial P}{\partial x} \right) \quad \text{Eqn. 1}$$

Eqn. 2

$$D(h) = D_1 \left[\alpha + \frac{1 - \alpha}{1 + \left(\frac{1 - h}{1 - h_c} \right)^n} \right]$$

where D_1 represents $D(h)$ when h is 100%, α is a parameter that represents the ratio D_0/D_1 where D_0 is the minimum $D(h)$ for $h = 0\%$, h_c is the pore humidity at $D(h) = 0.5D_1$ and n is an exponent. Here $\alpha = 0.05$, $h_c = 0.80$ and $n = 15$ are assumed [5]. Despite the fact that D is dependant on numerous factors, such as the ambient temperature and humidity, the main influence on D is the internal concentration, or the internal RH in this case. This equation calculates D , initially constant (up to approximately 85%) but it rapidly decreases to approximately 75%, where it remains constant thereafter, as shown in Fig. 3(a).

This equation gives a good representation of the actual moisture movement in the concrete during drying where initially the saturated conditions allows the moisture to 'diffuse' through the pores easier than when the moisture condition in the concrete changes to an unsaturated condition, particularly when the RH falls below 60%. Values for D shown in Fig. 3(a) are based on previous published data and calibrated for the model to best suit the experimental results. Previous authors [5, 6, 7] have suggested D lies between 10^{-9} to 10^{-11} m²/sec for normal dense concretes with w/c ratios between 0.4 and 0.6 during drying. D for the three w/c ratios are different due mainly to two factors. As the w/c rises, the amount of capillary pores increases as, theoretically speaking, only a w/c ratio of 0.44 in a sealed environment is required for full hydration and with a rise in capillary pores, the rate of moisture movement also increases. Secondly, as drying proceeds, the rate of moisture movement will decrease, as the change from saturated conditions early on to non-saturated conditions later causes a decrease in moisture diffusion, as shown in Fig. 3(a).

The evaporation through the surface is expressed by the convection coefficient (K), which is driven by the difference between the boundary (ϕ_B) and the environmental humidity (ϕ_E), as shown in Eqn. 3,

$$J = K(\phi_B - \phi_E) \quad \text{Eqn. 3}$$

where J is the mass flux of moisture through the surface [4]. DIANA allows the user to input the convection coefficient as a constant, a function of time or the boundary humidity or both. Typical values suggested ranging between 10^{-7} to 10^{-8} m/sec [8, 9] and the model here has been calibrated using these suggested values by means of a parametric study to best suit the experimental results. As expected, the evaporation rate from the slabs in the controlled room are higher than those in the laboratory, due to the greater humidity gradient between the concrete and the air in the controlled room. The evaporation rates used in the FE analysis for the slabs in the laboratory and in the room is shown in Fig. 3(b). The initial rate of evaporation from both slabs is quite high but, over time, decreases as the RH gradient between the concrete and the ambient air slowly converges when,

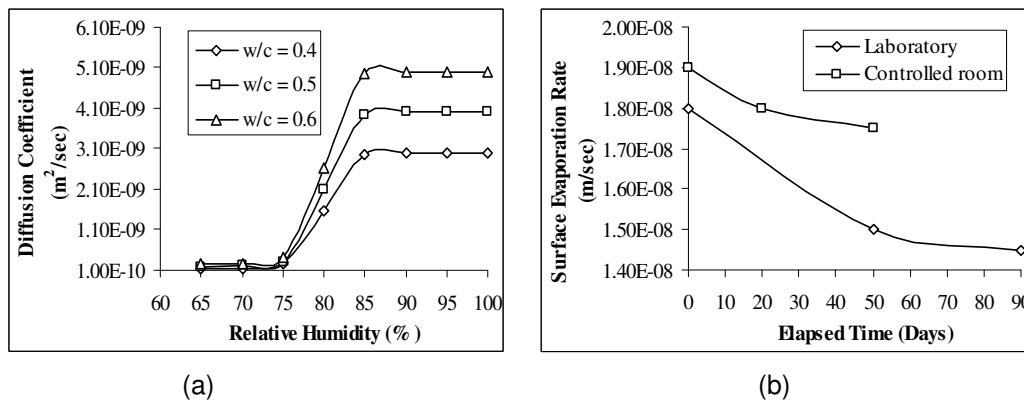


Fig. 3 Typical diffusion (a) and evaporation rates (b) used in the FE analysis.

theoretically, drying will cease. The K values shown in Fig. 3(b) are only given for the first 50 and 90 days in the controlled room and the laboratory respectively, as after this point in time, the impervious covering was applied.

FINITE ELEMENT RESULTS

This section presents the results from the FE analysis performed on the floor slabs using the mesh and material properties described earlier. The results are split into two sections. Firstly, the results from the drying concrete are presented and compared with the experimental results for the corresponding slabs drying in the laboratory and in the controlled room. In addition to the FE results for the 150mm thick slabs, some results from FE analysis performed on 100 and 200mm thick slabs will also be presented ($w/c = 0.5$) after 100 and 40 days drying in the laboratory and controlled room respectively. These show that the thickness of the slab is also a deciding factor in both the time to apply coverings and the humidity profiles through the depth of the slab [1]. This analysis is continued for the 150mm thick slabs until the surface reaches a humidity of 75%. At this point, the surface boundary condition is changed to account for the application of an impermeable floor covering and the analysis shows the covering's effect on the residual moisture in the concrete until equilibrium is reached in the concrete.

Drying Analysis

Fig. 4 shows an example of the FE results at various times (in days) compared with the experimental results. As shown there is a good correlation between both sets of results with a maximum difference of less than 6% between the results. For the slabs drying in the controlled room, similar results are shown. In terms of applying the floor covering, Figure 4 shows that there is very little difference between the experimentally measured and the FE predicted times to apply the covering, ie when the surface reaches a RH of 75%. Another important aspect that must be considered is the moisture profile through the depth of the concrete as both these aspects are vital to the application of the covering and their effect on the residual moisture over time. This is particularly relevant for the slabs in the controlled room.

Fig. 5 shows the results from similar FE analysis on 100 and 200mm thick slabs ($w/c = 0.5$) after drying for 100 and 40 days in the laboratory and the controlled room respectively with similar conditions as the 150mm thick slabs [1]. The results show that the thickness of the slab is also a factor that should be considered in terms of its affect on the drying time and the humidity distribution through the depth. It is clear that the 100mm thick slab is drying quicker than the 150 and 200mm slabs in both the laboratory and the controlled room.

Covering Analysis

The difference in model set-up for this type of analysis is two fold. Firstly, the evaporation boundary condition is removed from the model, as the covering is now effectively sealing in all residual moisture. Therefore, a 'no flow' boundary condition at the surface must be specified. Secondly, the initial condition for the model is taken from the RH profile when the surface reaches 75% RH, (previously set at 100% at the start of drying), taken either from the experimental results or the FE results for future prediction of the moisture redistribution in the floor slab. The only material property used in this analysis is the diffusion coefficient, whose variation will be identical to that used in the drying analysis, accepting that the RH will now be increasing in the top half of the slab. DIANA will still interpret D for the RH values as it varies inside the slab. Fig. 6 shows the FE results (in days) from the model after the covering is applied in the slabs dried in the laboratory and the controlled room.

For example, Fig. 7 shows the FE predicted times for equilibrium to occur for the slabs ($w/c = 0.5$) in the laboratory (over 220-days) and the controlled room (over 750-days) respectively, that is, when the RH through the depth of the slab is equal. In some cases, problems with floor coverings may not occur until several years after its application, where, in the controlled room it has taken just over 2-years for equilibrium to occur, compared with 220-days for the laboratory based slab. As shown, the final RH equilibrium in the slabs is 77.3% (laboratory) and 81.6% (controlled room), both greater than the 75% RH specified in the BS [2]. The effect of this is that a vapour pressure gradually builds up under the covering over time (Fig. 8) [3].

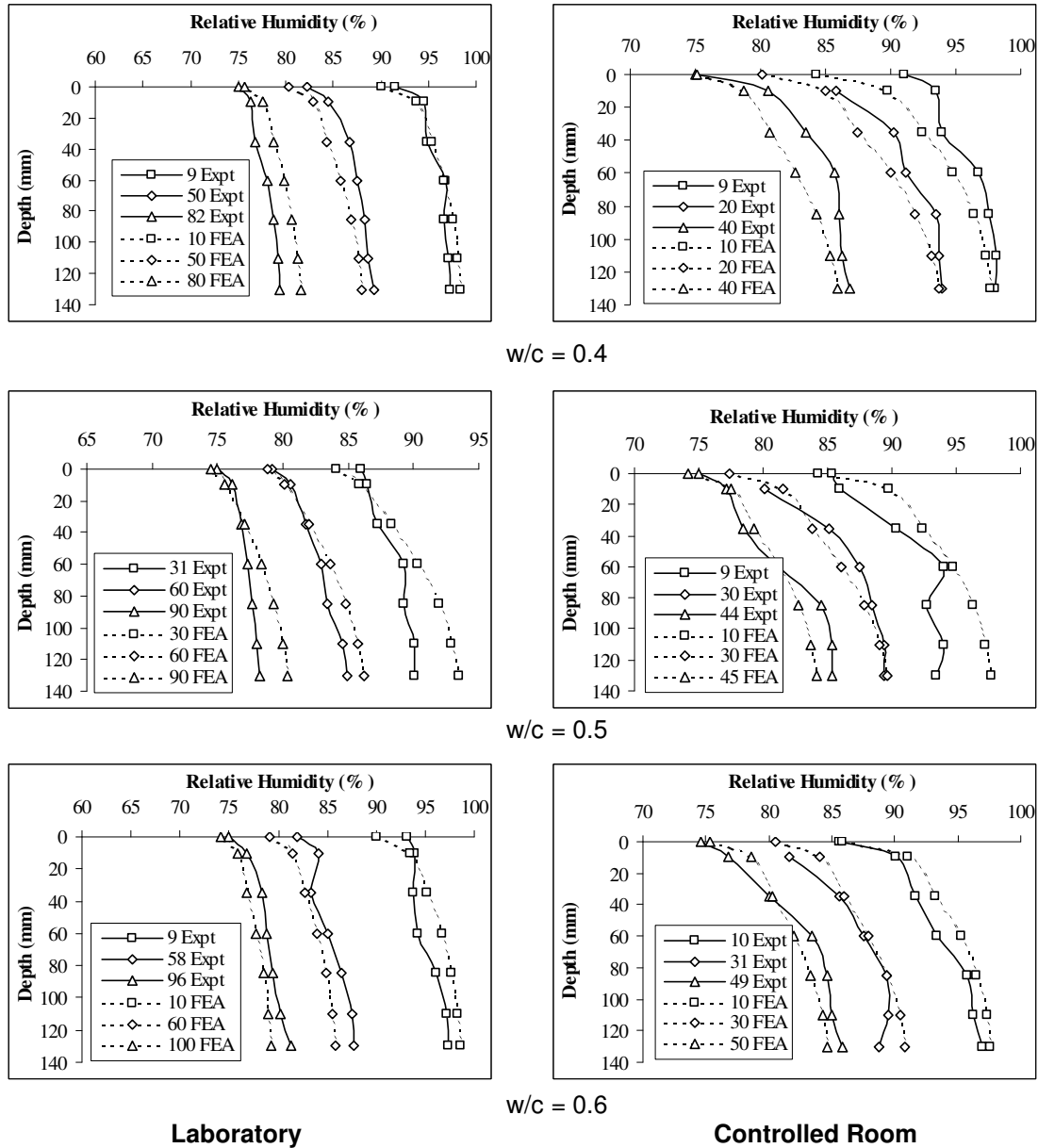


Fig. 4 Comparison between the FE analysis and the experimental results for the slabs ($w/c = 0.4, 0.5$ and 0.6) drying in the laboratory and the controlled room over time.

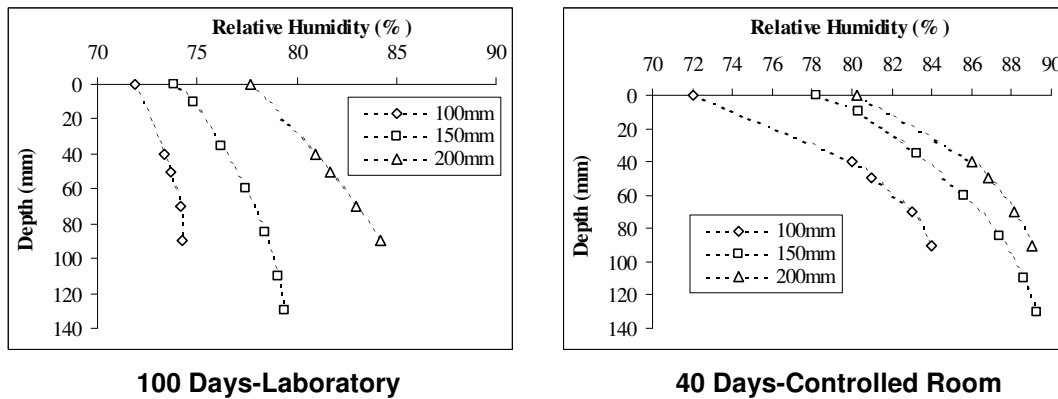


Fig. 5 FE results for the 100, 150 and 200mm thick slabs ($w/c = 0.5$) drying in the laboratory and the controlled room at 100 and 40 days respectively [1].

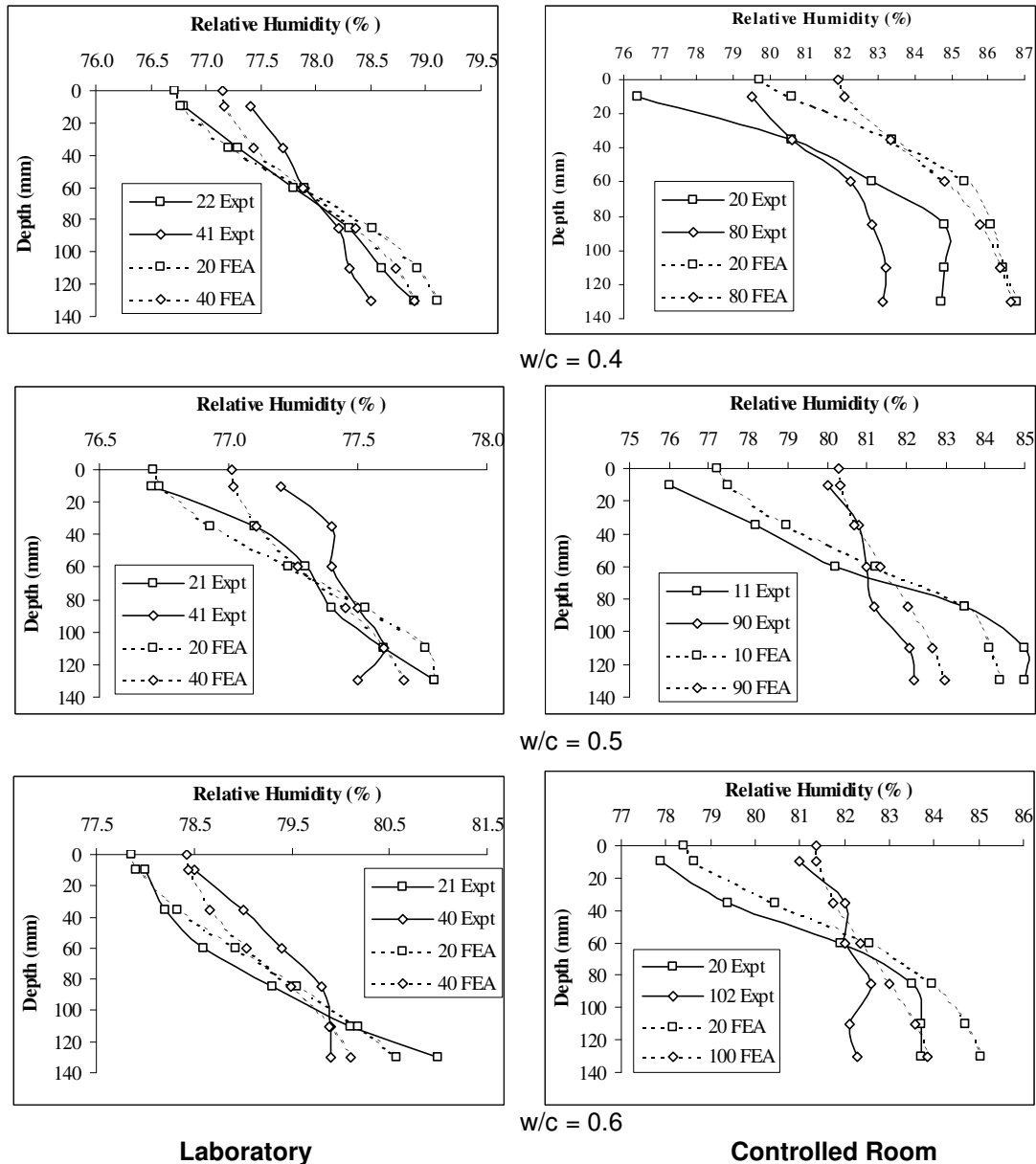


Fig. 6 Results from the experimental and finite element analysis after the covering is applied for slabs dried in the controlled room for w/c ratios of 0.4, 0.5 and 0.6.

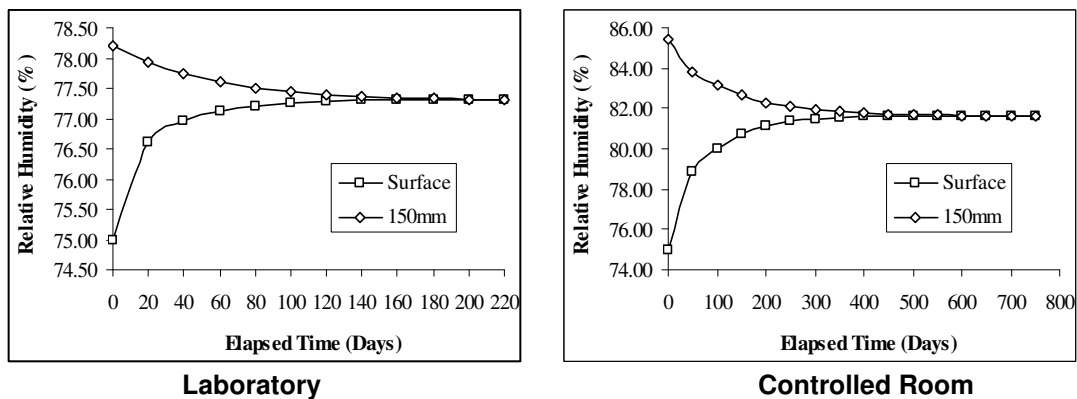


Fig. 7 FE predicted time for moisture equilibrium to occur in w/c = 0.5 slabs in the laboratory and in the controlled room.

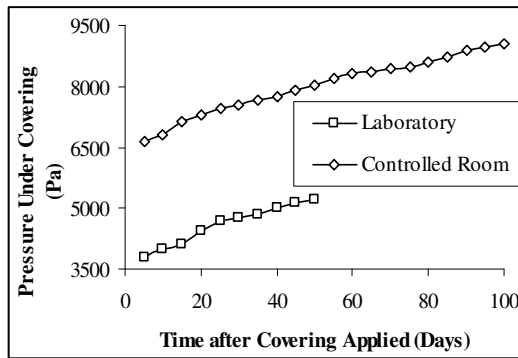


Fig. 8 Measured increase in pressure under covering in the laboratory and controlled room slab (w/c = 0.6) [3].

CONCLUSIONS

This paper presents results of the internal RH from FE analysis on a number of concrete floor slabs with various w/c ratios, thickness and drying environments, before and after the application of an impermeable covering. The results from the analysis have compared well with experimental measurements of the RH at various depths in the slab over time. Using non-linear diffusion coefficients and evaporation, it has been shown that the FE method can accurately predict the changing moisture profiles initially during drying and the redistribution of residual moisture in a floor slab after the application of an impermeable floor covering.

The main influences on moisture movement during drying, in terms of the point in time to apply floor coverings (or the time to reach 75% surface RH) and the RH profiles through the depth are the w/c ratio, the thickness of the slab and the environmental conditions. By using previously published non-linear diffusion coefficients and evaporation rates, a series of parametric studies have determined the material properties to give the best comparisons with the experimental results. Also, by specifying the environmental conditions, and in conjunction with other specific studies into mesh fineness, time-stepping sizes, integration schemes and solution routines, the FE model has been shown to be a very capable and useful tool in predicting the moisture movement through concrete over time on 100, 150 and 200mm thick slabs drying in both a natural (laboratory) and accelerated (controlled room) drying conditions with w/c ratios of 0.4, 0.5 and 0.6 [10].

The advantage of this model is that flooring contractors will be capable of accurately predicting the RH profiles in concrete at any point in time through the depth of the slab and, more particularly, when the surface reaches 75% RH, previously determined by surface hygrometers [2]. In addition to this, the prediction of the long-term effect on the residual moisture, after applying an impervious covering, has been shown to give good correlations with experimental results. This will allow the contractor to assess the safe point in time at which to apply a covering to avoid future damages caused by excessive residual moisture (and vapour pressures) in floor slabs, the evidence of which have increased over the past 30-years due to fast-track construction practices.

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